Additive Manufacturing for Property Optimization for Automotive Applications

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Project ID#: mat200

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Overview

Timeline

- Project start date: Oct 2020
- Project end date: Sept 2023
- Percent complete: 50%

Budget

- DOE project funding: $500K/yr
  - DOE: 100%
- Funding for FY21: $500K

Project Partners

- Ford Motor Company: Industry Partner
  Project Lead: Ellen Lee
- UCLA: Subcontract
  Project Lead: Xiaoyu (Rayne) Zheng

Barriers and Targets

- **Barriers:** (1) Lack of understanding of properties with respect to fracture and energy absorption*, (2) Lack of predictive engineering and modeling tools*, (3) Cost/availability of most lightweight materials and current manufacturing processes are not competitive*.

- **Targets:** (1) Design, optimization, and performance simulation of tailored 2.5D cellular structures for extrusion-based AM incorporating ML, and (2) Fabrication and performance evaluation of parts printed using the multi-material BAAM system and OPP technology.

* Ref.: Light-Duty Workshop Final Report (DOE-VTO)

Relevance

Overall Objectives

Combine multiple technologies associated with Additive Manufacturing (AM) to increase the performance and reduce the manufacturing cost and weight of components using composites

VTO’s Mission

Reduce the transportation energy cost while meeting or exceeding vehicle performance requirements

Current Limitations

- Design constraints with conventional manufacturing methods → AM enables tailoring lattice designs to satisfy multiple conflicting requirements for large automotive subcomponents
- Design requires a series of stress simulations – design modification cycles → Machine Learning (ML)-based design
- AM provides design flexibilities in 2D but still has constraints in 3D → Out-of-plane printing to allow more design flexibility
- AM for large scale utilizes single material deposition for large scale printing → Multi-material printing

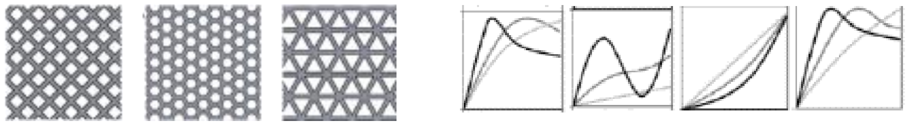
Our Strategies

- **Optimize large-scale structure** for structural design and multi-material placement printed in BAAM or mid-scale printer.
- Develop the **control technique** of an **out-of-plane printing** and fabricate a subcomponent of a vehicle.
- Develop **Machine Learning (ML) algorithm** for the automotive subcomponent design with lattice structures and tailored energy absorption characteristics.

Approach

MATERIAL & DESIGN OPTIMIZATION

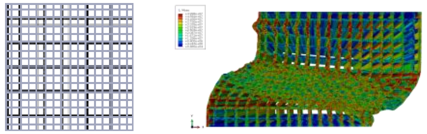
Tailored Lattices & Multi-Materials



Lattice Structures with Tailored Stress-Strain Response

Fiber-Reinforced Thermoplastics, Elastomers, Thermoplastic Foams, Polymer Blends

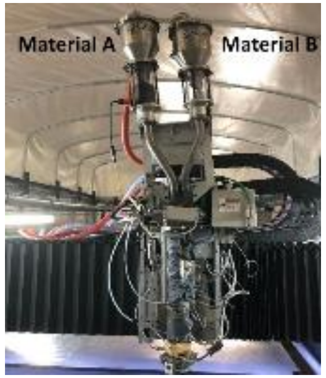
SIMULATION



Deformation Prediction
Strength/Stiffness Prediction

ARTIFICIAL INTELLIGENCE

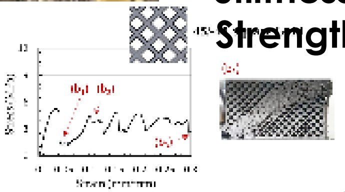
FABRICATION (Extrusion AM)



Out-of- Plane AM
Single Material (Mid-Scale)

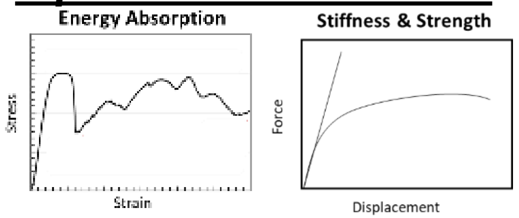
TESTING

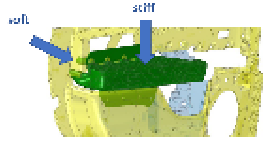
Mechanical Properties such as Energy Absorption, Stiffness, Strength



PERFORMANCE

Multi-Property Optimized Structures





Milestones

			Y1				Y2				Y3			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	T1.M1	**Part design** selection based on discussions with the industry partner (e.g., frontal bumper)												
	T1.M2	**Load cases and criteria** for mechanical responses (e.g., deflection and energy obsorption)												
	T1.M3	**Mechanical property evaluation** for BAAM materials.												
	T1.M4	**Material composition optimization** for BAAM printed structures.												
	T1.M5	**Scalability test** of the of the structure from small-scale prints to BAAM												
	T1.M6	**Toolpath optimization** for the latticed structures for BAAM with multi-material												
	T1.M7	Demonstrate **printing** of performance optimized multi-material structures on the BAAM system												
	T1.M8	Mechanical **testing and evaluation** of a BAAM printed structure												
Task 2	T2.M1	**Part design** selection for out-of-plane printing with the industry partner (e.g., door arm rest)												
	T2.M2	Define **load cases and criteria** for mechanical responses (e.g., deflection and energy obsorption)												
	T2.M3	**Performance simulation** for the out-of-plane structure												
	T2.M4	Material **property evaluation** for a multi-axis extrusion system												
	T2.M5	**Slicing technology** development for the multi-axis extrusion system												
	T2.M6	**Toolpath planning** for the out-of-plane structure												
	T2.M7	**Robot arm control & extrusion control** optimization for the multi-axis system												
	T2.M8	Demonstrate **printing** of an out-of-plane property optimized structure												
Task 3	T3.M1	Development of a **simulation technique** for 3D-printed lattice structures												
	T3.M2	**Calibration** of the simulation **parameters** (small-scale)												
	T3.M3	**Perform simulations** for multiple lattice structuers and material combinations (small-scale)												
	T3.M4	**Mechanical tests** for multiple lattice structures and material combinations (small-scale)												
	T3.M5	Development of an **ML Approach** & **Training Data Acquisition** for lattice structures												
	T3.M6	Generation of **Tailored Lattice Structures** and Evaluation (small-scale)												
	T3.M7	Lattice structure combined with **self-sensing material** (small-scale)												
	T3.M1-6	Regular milestones for BAAM and stretched milestones for out-of-plane printing structure												

June 2022

“ Any proposed future work is subject to change based on funding levels”

Task 1: Design optimization for a multi-material bumper

Material properties characterization of selected materials

Completed | In-Progress

	Properties	Tasks Progress Status														
		Printing					Machining					Testing				
Primary Properties	Tensile Modulus	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy
	Tensile strength	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy
Secondary Properties	DMA- Modulus vs frequency: Torsion	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy
	DMA- Modulus vs frequency: Flexural	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy	CF/ABS	TPU	90-10 Blend	80-20 Blend	Xenoy

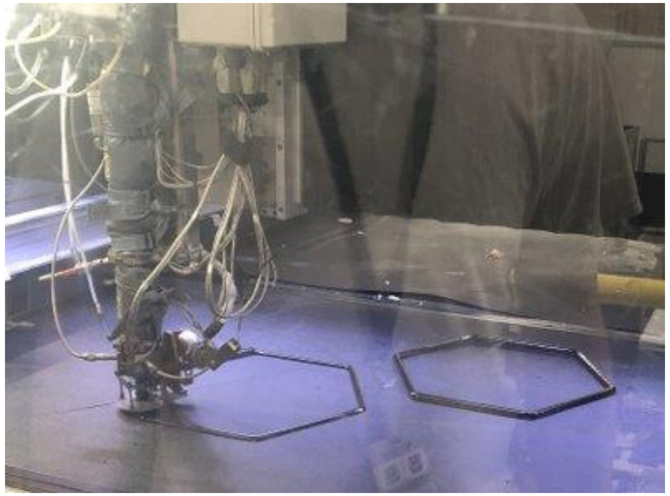
- Characterization of basic material properties was conducted on selected materials for design optimization.
- Materials chosen covered a range of properties, from highly stiff systems (20 wt.% CF/ABS) to highly flexible systems (TPU), as well as systems with properties in-between (90:10 and 80:20 blends of TPU & 20 wt.% CF/ABS)
- Xenoy® 1102, a material typically used for bumpers, was selected as the baseline material.
- Test structures were printed on the large-scale printer (BAAM) with all the chosen materials and test coupons were machined from the printed parts to characterize material properties per ASTM standards.

Task 1: Design optimization for a multi-material bumper

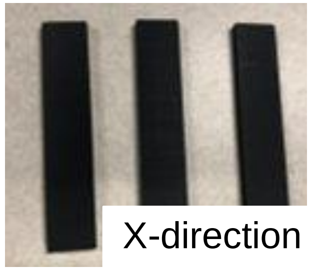
Material properties characterization of selected materials

Printing on the BAAM & machining of test coupons for mechanical testing.
Representative images for Xenoy® 1102 parts.

Hexagons printed on the BAAM to harvest mechanical test coupons



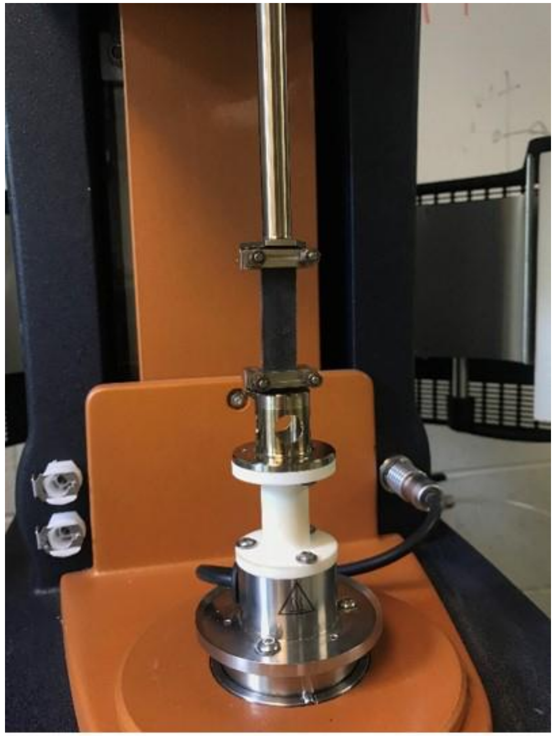
Dynamic mechanical analysis (DMA) coupons machined from printed hexagons



X-direction

Z-direction

DMA testing in torsion mode



Tensile test coupons machined from printed hexagons

X-direction

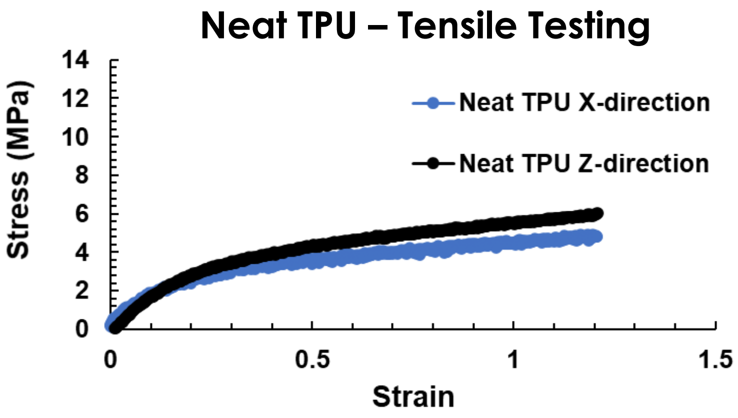
Z-direction

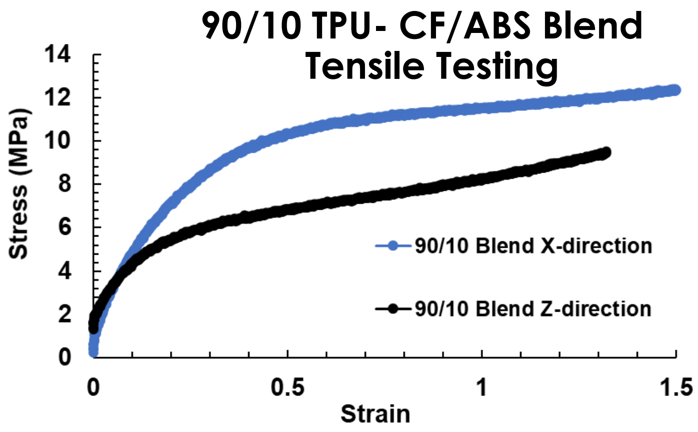
X-direction: Along print direction, Z-direction: Transverse to print direction

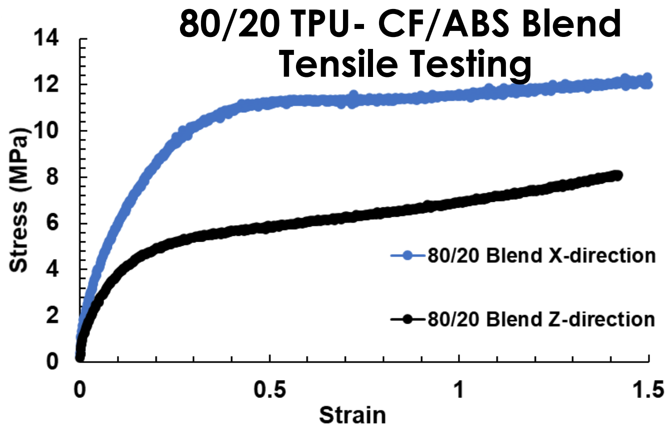
Task 1: Design optimization for a multi-material bumper

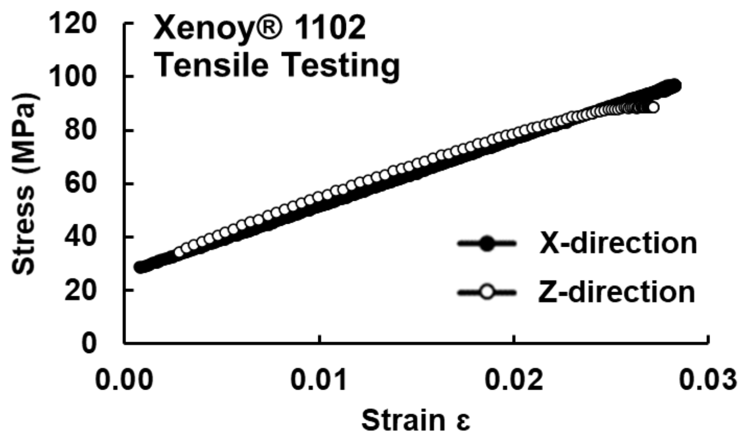
Material properties characterization of selected materials

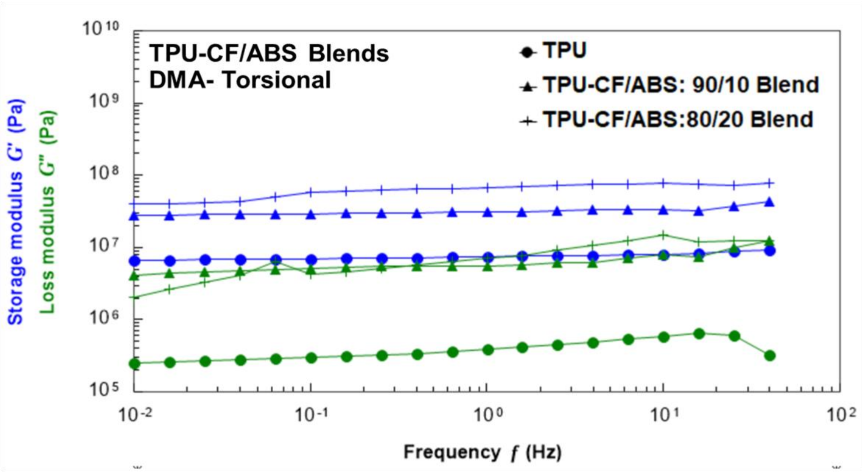
Representative data for tensile testing and Dynamic Mechanical Analysis (DMA) of selected materials

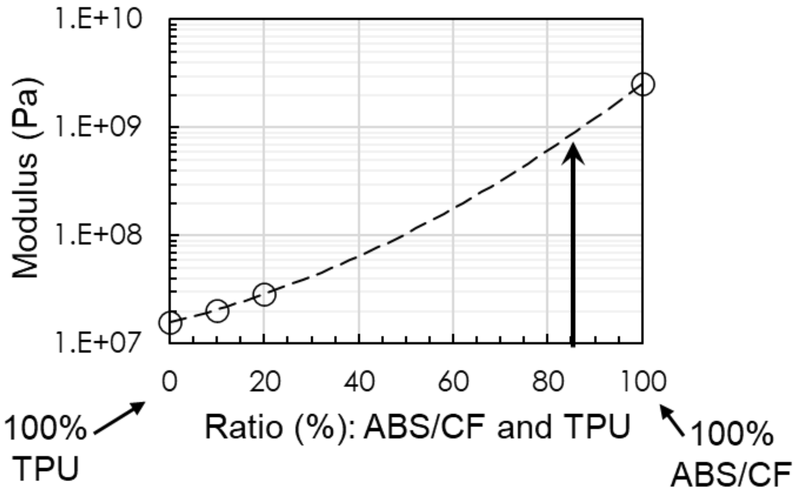








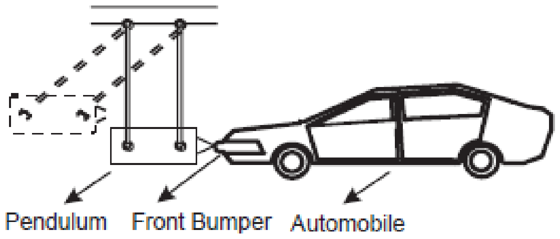




Using blends and multi-material systems offer a wide range of tunability in material properties and thus, design flexibility for the final part

Task 1: Bumper design, slicing and toolpath optimization

Bumper design involves multiple conflicting performance requirements

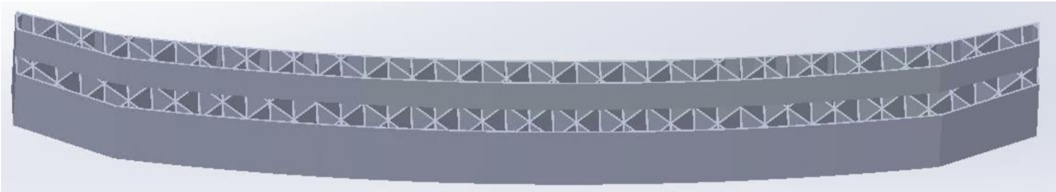


Pendulum test

Large footprint impactor at low speed (1m/s)

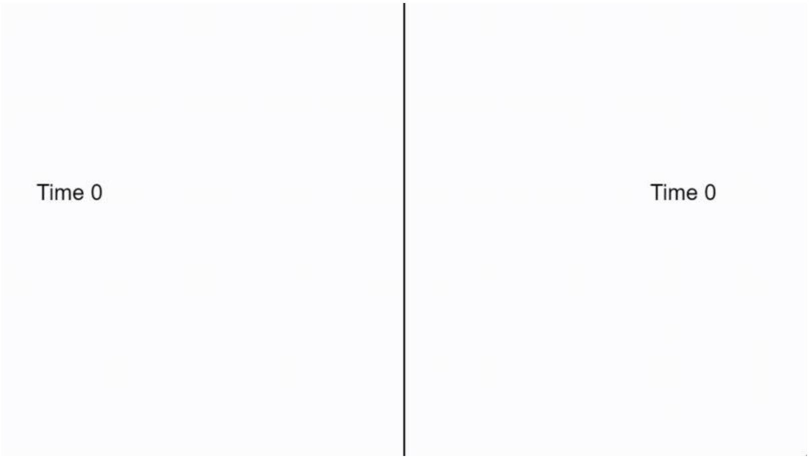
Leg flexion test

Small footprint impactor at high speed (11.1 m/s)



Preliminary bumper design using triangular lattice structure

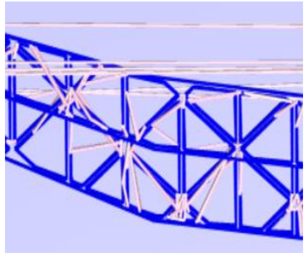
Toolpath optimization for printing lattice structures

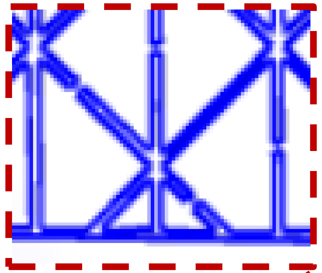


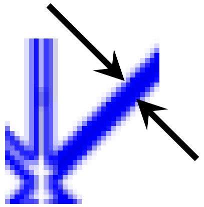
Continuous toolpath algorithm developed at ORNL

Conventional toolpath

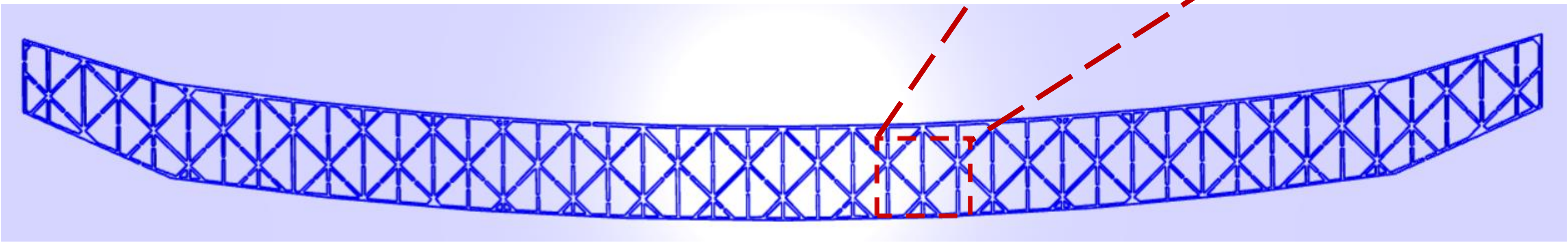
Continuous toolpath





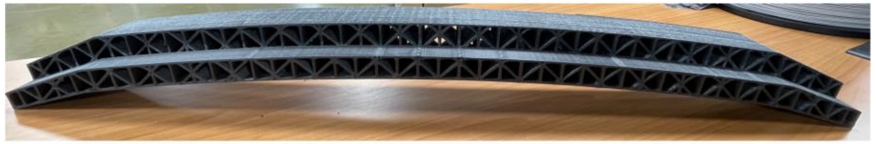


Mid-scale printer instead of BAAM as strut is too thin



Task 1: 3D printing of bumper and drop tower testing of lattices

Multi-material printing of a full-scale bumper on a mid-scale 3DP Printer



} CF/ABS/TPU
} CF/ABS

Bumper features (Dimensions: 108 x 13 x 10 cm):

- 3DP filament-based printer
- CF/ABS and CF/ABS (85%) – TPU (15%) blends
- Custom made filaments from Push Plastics

Challenges resolved:

- Filament is too brittle and braking while printing
- Poor filament quality (moisture) – oven drying

Multiple conflicting design requirements for bumper:

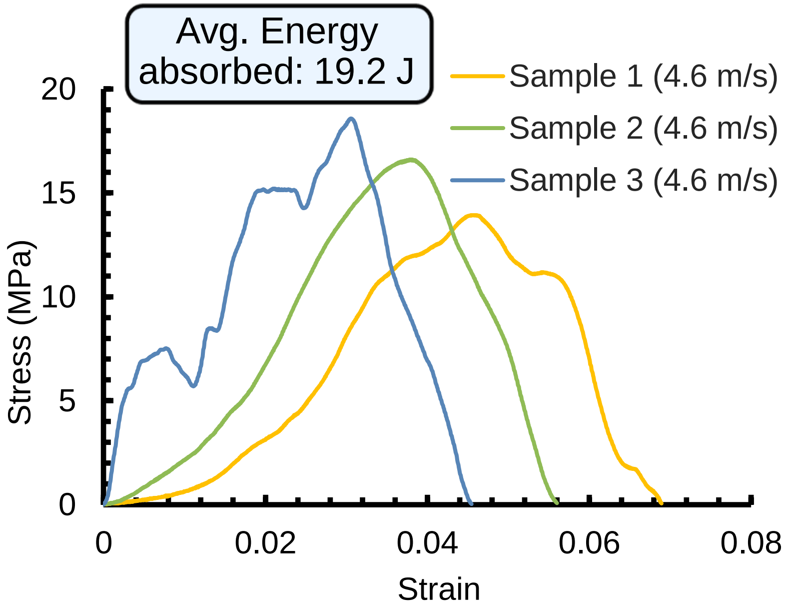
Impactor Details	Low Speed Impact	High Speed Impact
Mass	1500 kg	13.6 kg
Velocity	1.1 m/s	11.11 m/s
Target energy to be absorbed	908 J	840 J

Drop Tower Testing ⟹

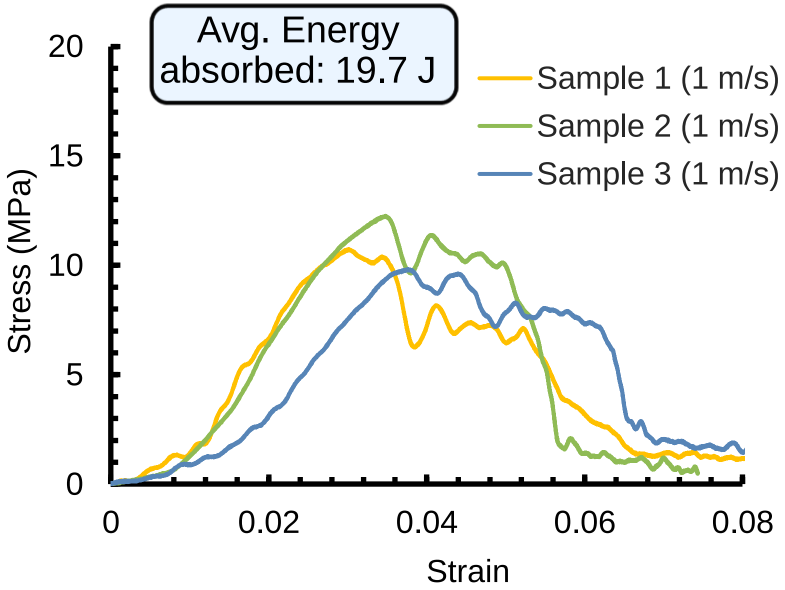
Unit cell

Unit cell in drop tower test fixture

High velocity impact



Low velocity impact



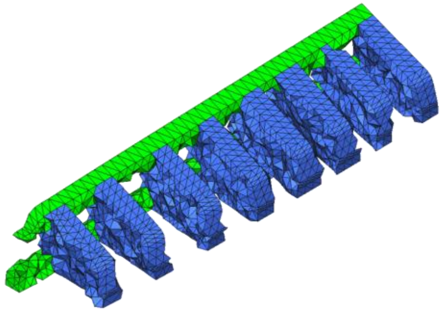
Evaluate energy absorption characteristics of different lattice types and material blend combinations

Task 2: Design and performance simulations for door armrest

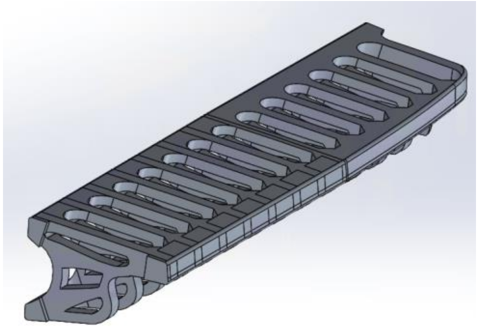
Load case and design criteria

Requirement: < 15mm deflection

Topology Optimization

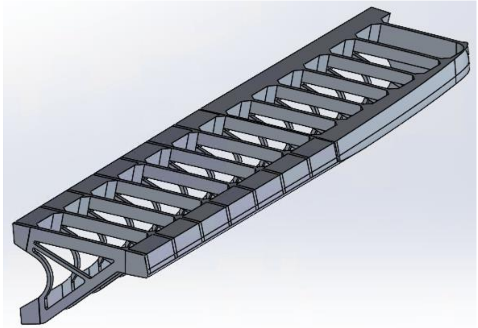


Design Iterations



Shell-based design

Weight = 274 g



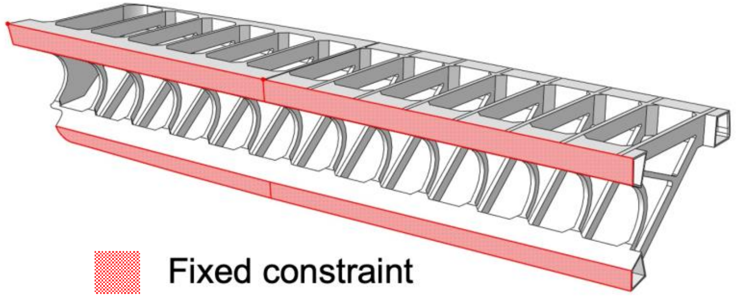
Strut-based design

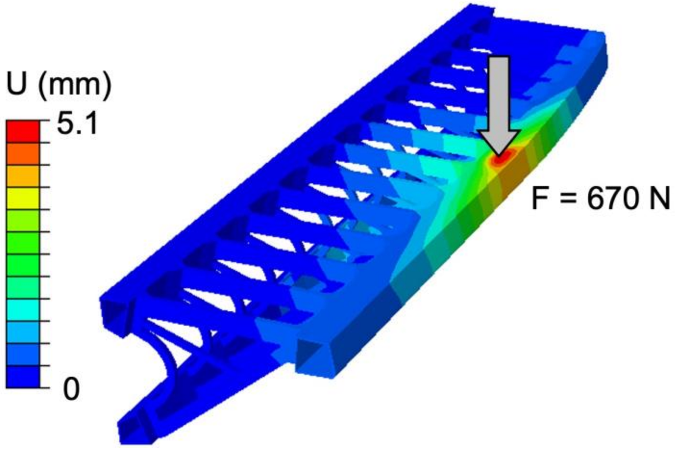
Weight = 234 g

Performance simulations on the strut-based final design

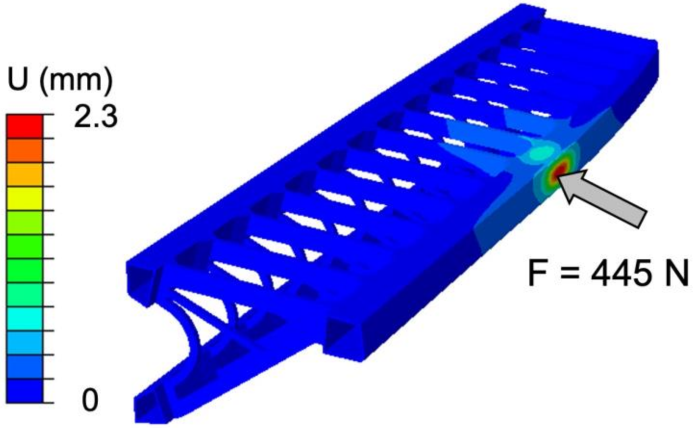
- Material Characterization: Polylactic Acid (PLA)

Elastic Modulus (GPa)		Tensile Strength (MPa)	
X-Average	Z-Average	X-Average	Z-Average
2.93	2.76	58.11	42.54





Max. deflection = 5.1 mm

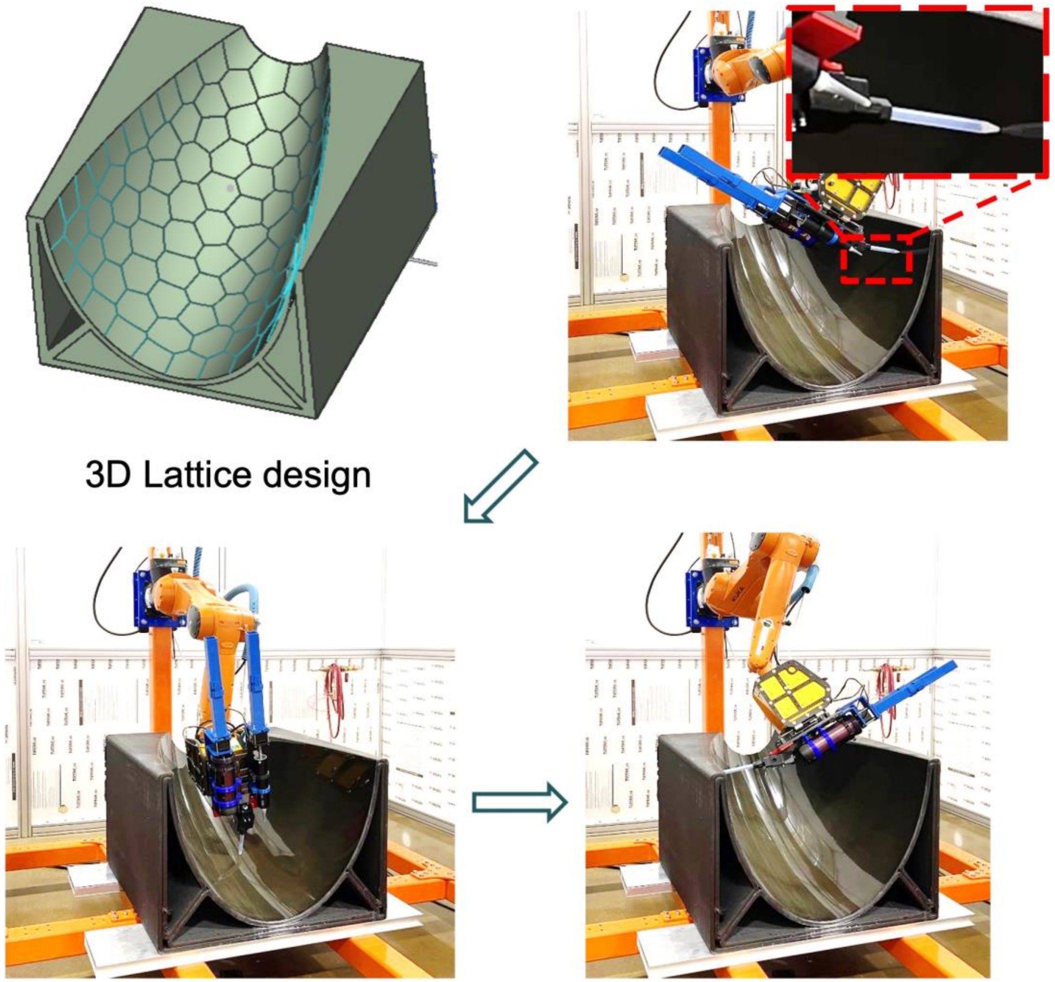


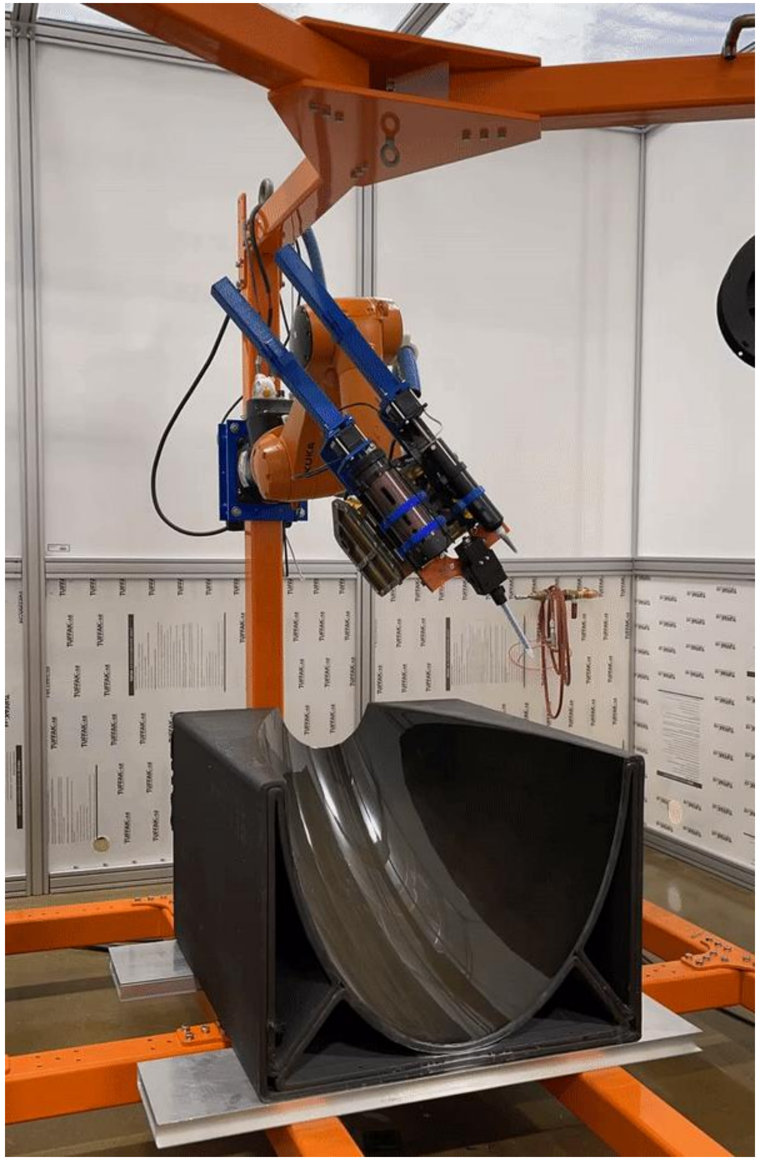
Max. deflection = 2.3 mm

Maximum displacement < 15 mm
Satisfies design requirement

Task 2: Out-of-plane printing technology developed at ORNL

- Out-of-plane printing of 3D lattice structure on curved surface

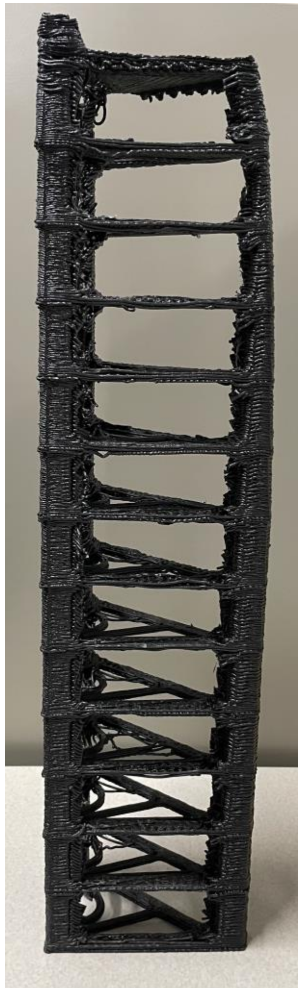




(fast play of animation)

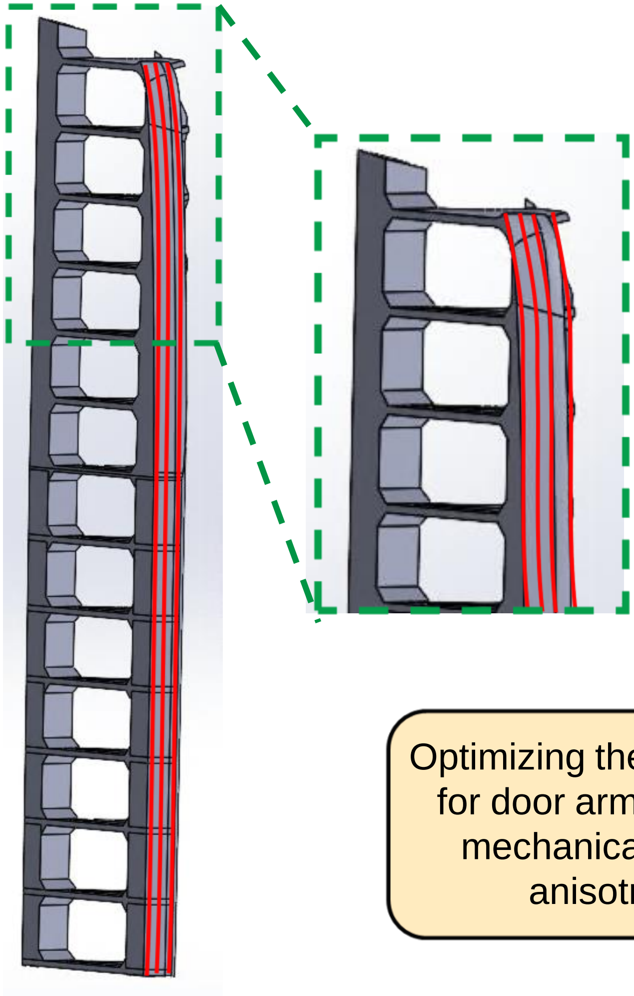
Task 2: Toolpath optimization and 3D printing of door armrest

In-plane printing of a door armrest using Orbital Composites robotic arm 3D printer

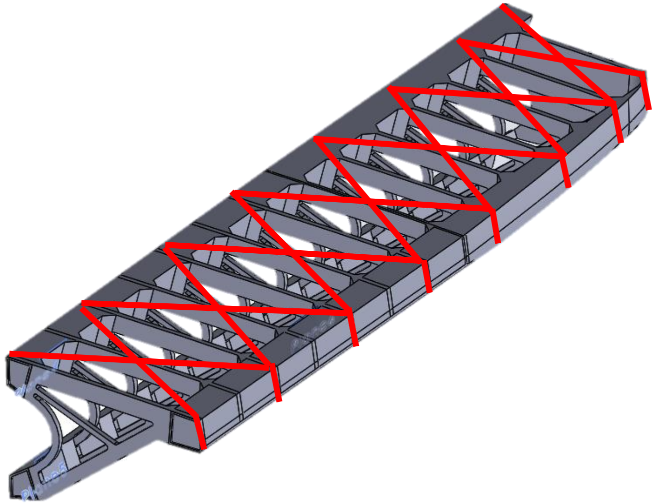


Toolpath planning, robotic arm control and out-of-plane printing (OPP) of door armrest

OPP on a curved surface



Wrapping the armrest using OPP

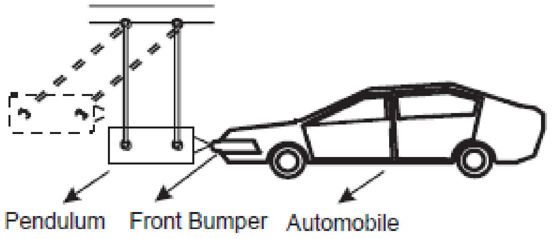


Optimizing the toolpath for out-of-plane printing for door armrest allows achieving enhanced mechanical performance overcoming the anisotropy in X- and Z-directions

Task 3: Design approach for multi-material lattice-based bumper

Pendulum test

Large footprint impactor at low speed (1m/s)



Leg flexion test

Small footprint impactor at high speed (11.1 m/s)

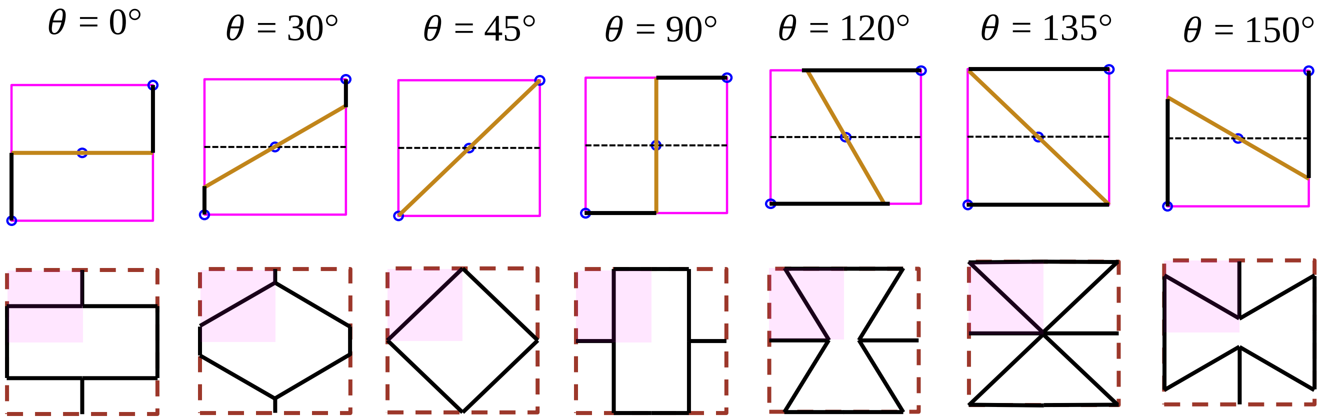
Design Approach for Bumper

Material design:
- CF/ABS – TPU Blends

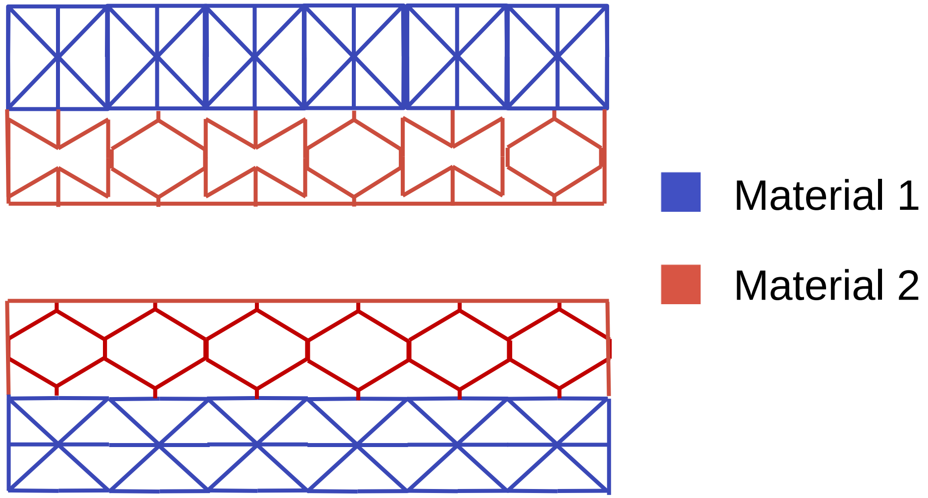
Lattice Topology:
- Lattice type and size
- Strut thickness (Relative density)

2D Architectural Genes for Training Data

Transformative via θ



Bumper designs with multiple materials and lattice types

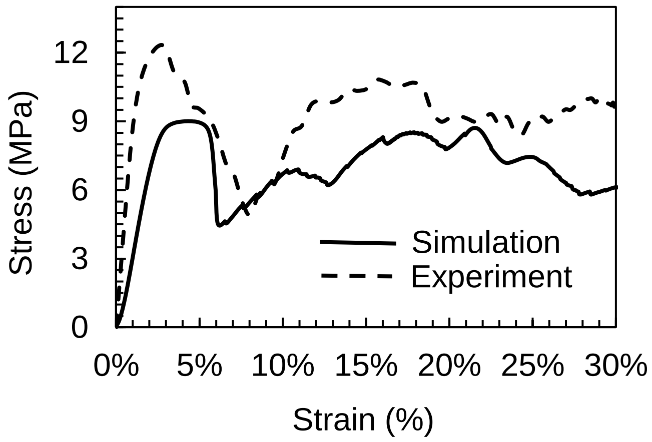


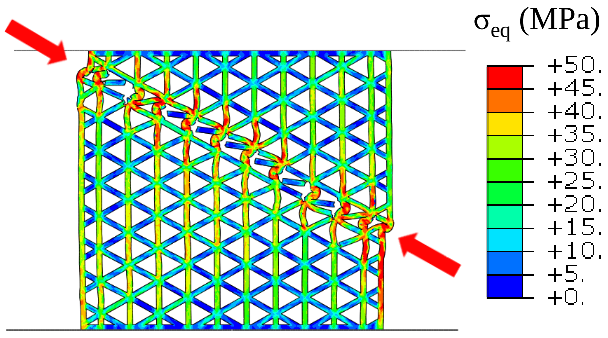
Task 3: Quasi-static and dynamic simulations on lattice structures

- Previous Year's Work: Quasi-static compression on fiber-reinforced composite 3D printed structures

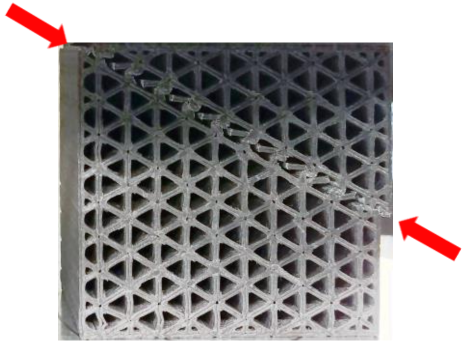
Triangular Lattice Unit

15 wt% CF/ABS





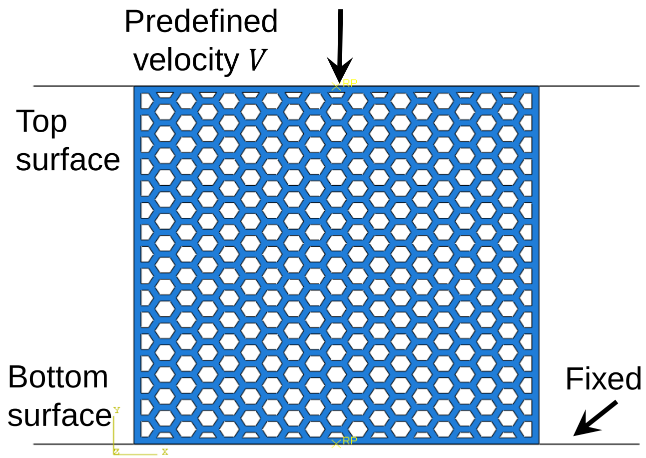
Simulation



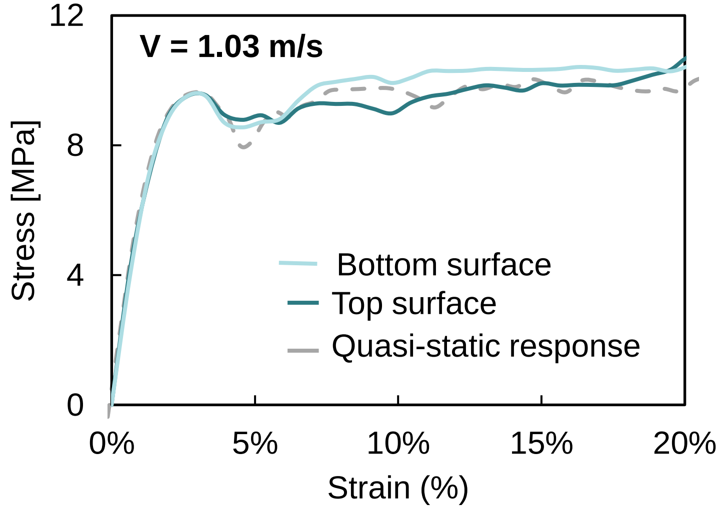
Experiment

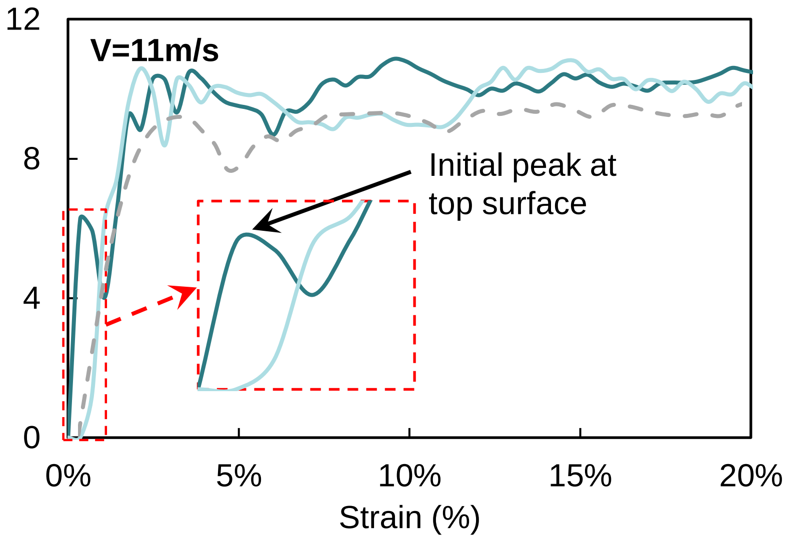
Initiation of failure under quasi-static loading

- Simulations for low and high velocity impact on lattice structures



Boundary Conditions

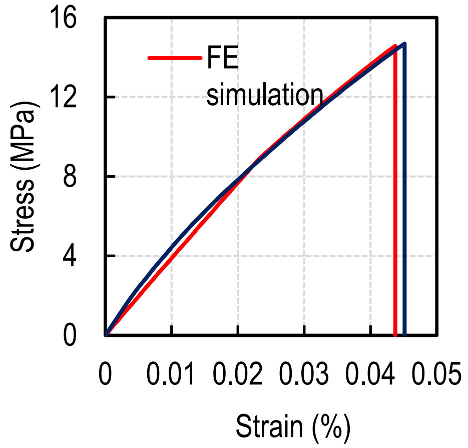




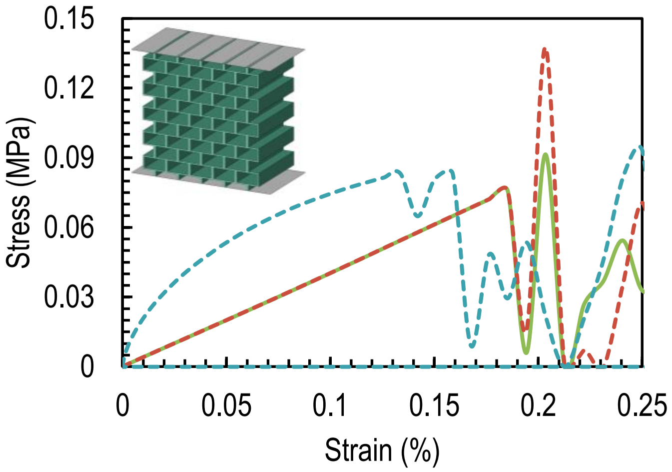
Stress-strain response depends on quasi-static or dynamic impact and distinct response for low and high velocities

Task 3: Dynamic simulations on lattice structures

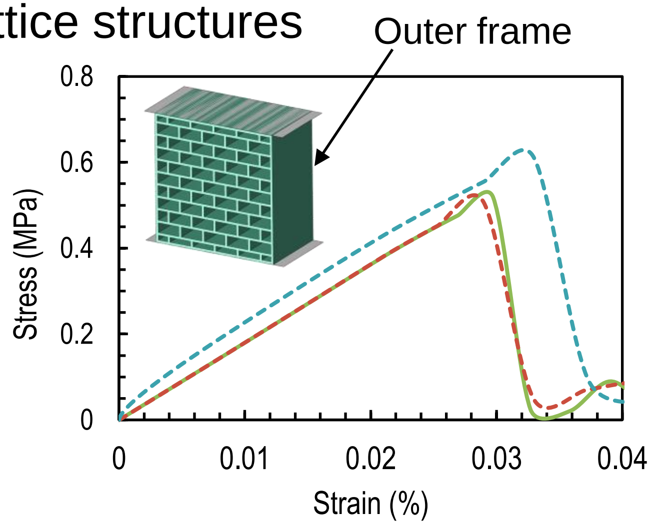
- Effect of outer frame on the dynamic response of lattice structures



Base material



Lattice structure with no outer frame

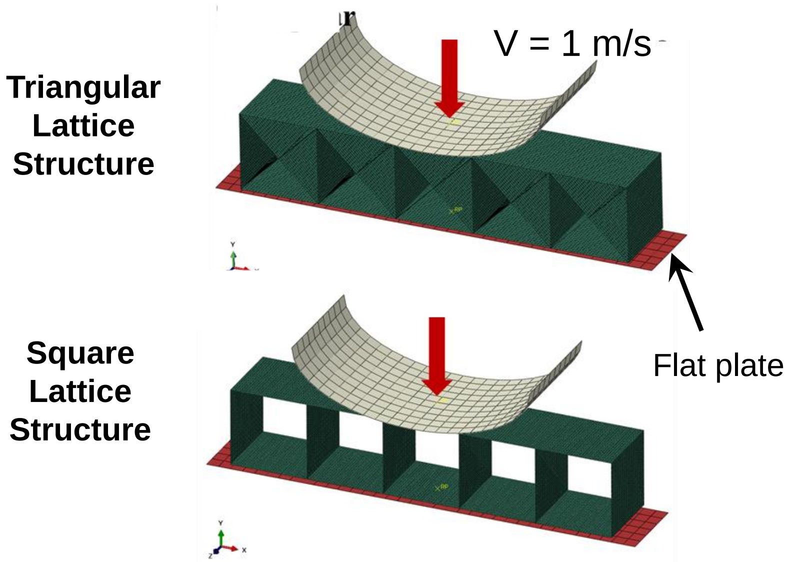


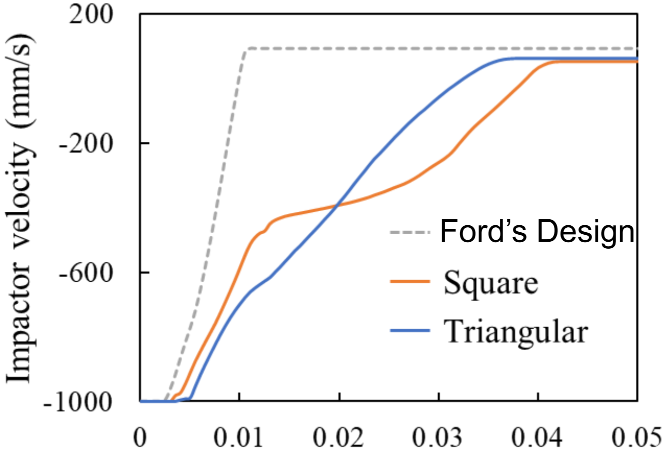
Lattice structure with an outer frame

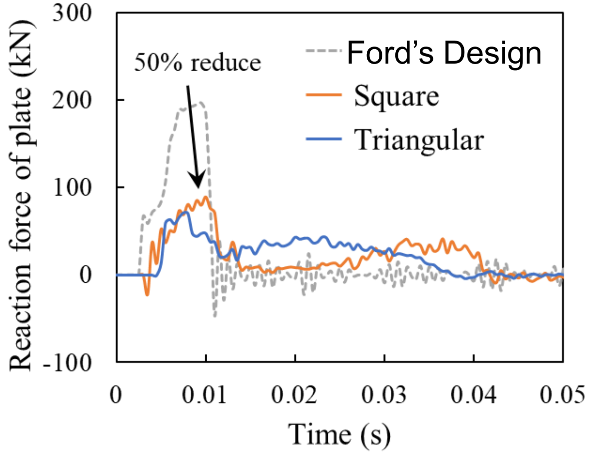
Lattice structure with outer frame leads to:

- Higher strength
- Lower failure strain
- Limited stress-strain curve tunability due to early brittle failure and less deformation freedom due to frame

- Comparing low velocity impact testing on different lattice structures with Ford's reference design



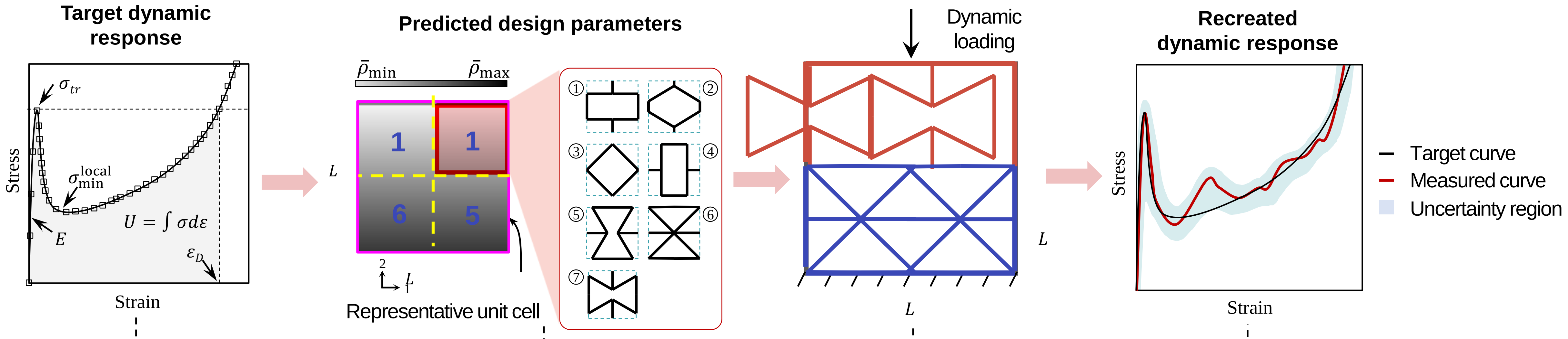




Preliminary investigation reveals that the lattice structures reduce the reactions forces and max. stress

Task 3: Simulations and design optimization using machine learning

- Machine Learning (ML) framework for tailorable dynamic behavior of frontal bumper



Input → **ML** → **Output** → **Digital model** → **Performance evaluation**

Target response parameterized as an evenly spaced vector)

Complete architectural description

I. Classification of structural gene type and size

II. Classification of material blend ratio

III. Classification of relative densities or strut thickness

ML-generated 2D lattice capable of replicating target behavior

Mechanical testing

(with 3D-printed sample made of the predicted digital model)

Responses to previous year’s reviewer's comments

- **What are the unique testing methods beyond standardized testing that have been employed?**
  - For material properties characterization, test coupons were machined from samples printed on large-scale system (BAAM) and mechanical testing was conducted as per ASTM standards used for polymers and composites testing.

- **What is the correlation between specific materials development approaches and the team’s optimization simulations with design?**
  - Developed CF/ABS TPU blends have tunable elasticity over an order of magnitude offering great design flexibility.
  - Tailorable material properties augment the topological design freedom and thus allows to satisfy multiple conflicting design requirements involved in the design of a bumper

- **What Artificial Intelligence (AI) methods employed can be specific to lightweighting and will include materials and design development?**
  - Sequential integrated strategy using multiple neural network models will be employed to predict lattice type, their relative density and material property and thus enables lightweighting (low relative density lattices) using multiple CF/ABS TPU material blends/choices developed.

- **“It would be great if mechanical testing can be in conjunction with DIC. The team may do in situ characterization during printing, if possible.” design development?**
  - In our previous work, DIC was used to measure deflection of walls during printing but negligible deflection was observed for the chosen material. Consequently, DIC would be used for in situ characterization if significant deflection is expected for different material blends.

Collaborations

- **Industry Partner:** Ford Motor Company
  - Point of Contact: Ellen Lee
  - Team Members: Iskander Farooq, Zach Pecchia, Sushmit Chowdhury, Mattew Rebandt

Technical Discussions and Experimental Testing:

- Inputs on the multiple conflicting design requirements for bumper design and simulation strategies
- Design review meetings for evaluating the frontal bumper and door arm rest designs
- Support on full-scale simulations for the entire car assembly with the designed frontal bumper
- Full-scale dynamic impact testing of 3D printed lattice bumper at the collaborator's facility

- **Subcontractor:** University of California, Los Angeles (UCLA)
  - Point of Contact: Prof. Xiaoyu Rayne Zheng
  - Team Members: Desheng Yao, Chansoo Ha

Machine Learning (ML) Framework Development :

- Drop tower impact testing on lattice structures for validation of numerical simulations
- Simulations on lattice genes to generate training data using material properties measured by ORNL
- Development and implementation of ML framework using deep neural networks for designing multi-material lattice-based frontal bumper

Proposed future research

- Task 1:
  - Mechanical characterization of CF/ABS TPU material blends to enable multi-material design
  - Slicing and toolpath optimization for multi-material printing of optimized design on a mid-scale 3D printer
  - Printing of performance optimized multi-material lattice structure based frontal bumper
  - Mechanical testing of lattice structures and full-scale bumper for performance evaluation

- Task 2:
  - Toolpath planning for out-of-plane printing of an armrest
  - Robotic arm control and extrusion control optimization for the multi-axis system
  - Printing of an out-of-plane property optimized armrest structure

- Task 3:
  - Simulations on lattice structures with different unit cell sizes, thickness, and materials to be used as training data in the sequential integrated machine learning framework
  - Development and implementation of machine learning framework for lattice structure design optimization of frontal bumper

“ Any proposed future work is subject to change based on funding levels”

Summary

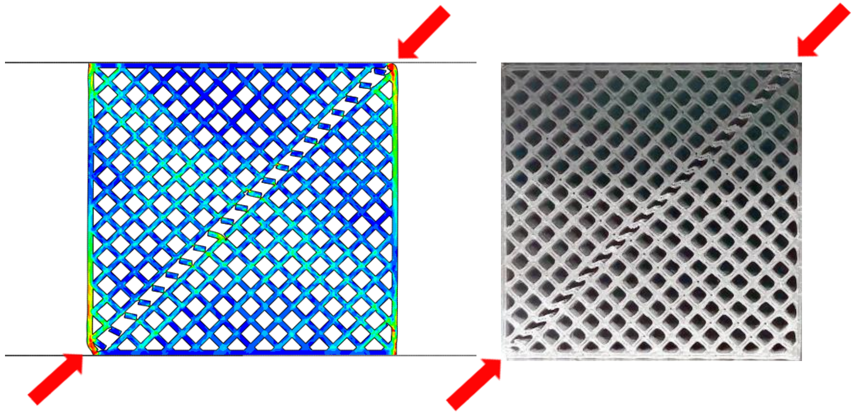
- Target:
  - Design, optimization, and performance simulation of tailored 2.5D cellular structures for extrusion-based AM incorporating ML, and
  - Fabrication and performance evaluation of parts printed using multi-material BAAM system and Out-of-Plane (OPP) technology to overcome anisotropy of polymer composite parts
- Progress:
  - Mechanical characterization was performed on multiple materials to identify suitable materials and material blends that provide a range of tunable properties for multi-material bumper
  - Full-scale multi-material frontal bumper was printed on a mid-scale 3D printer
  - Design armrest using topology optimization and 3D printed on a robotic arm-controlled printer
  - Developed a simulation framework to study mechanical response of fiber reinforced composite lattices with different topologies
  - Drop tower experiments and dynamic impact simulations on multiple lattice structure types have been performed
  - Machine learning framework for designing a lattice-based multi-material bumper with tailorable dynamic behavior was identified

Technical Backup Slides

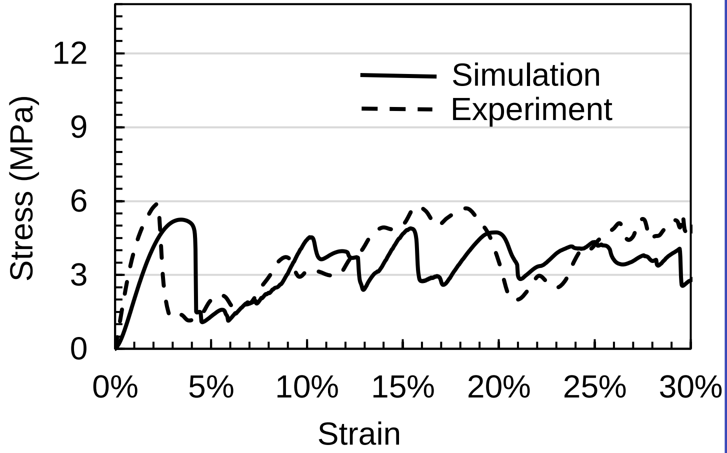
Task 3: Compression characteristics of lattice composite structures

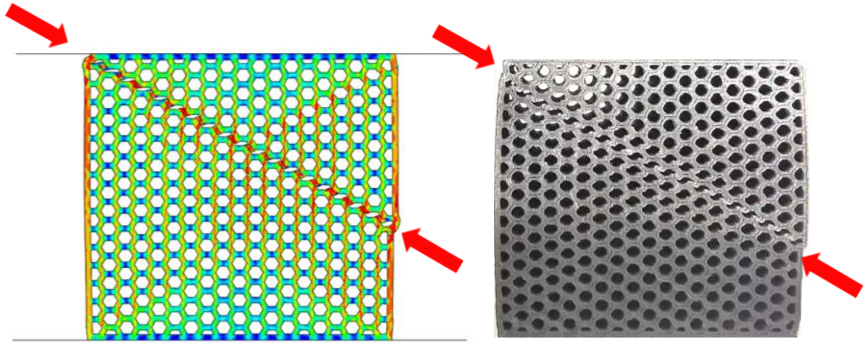
- (Previous Year's Work): Quasi-static compression on fiber-reinforced composite lattice structures

  S. Kim, A. Nasirov, V. Kishore, C. Duty and V. Kunc. Compression characteristics of additively manufactured lattice composite structures (Manuscript in preparation).

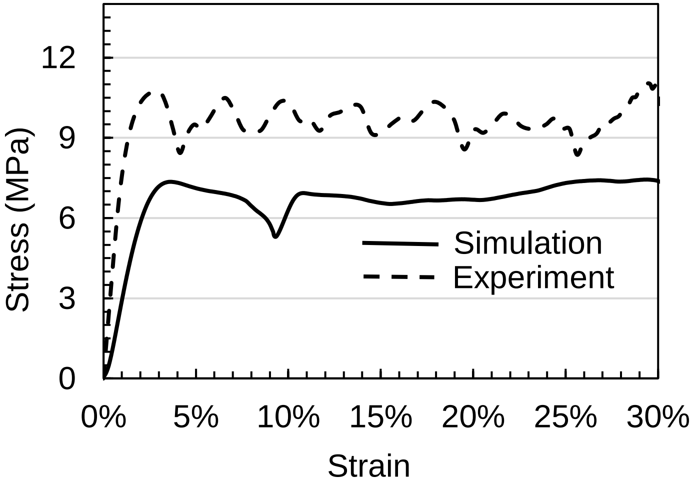


Diamond lattice structure

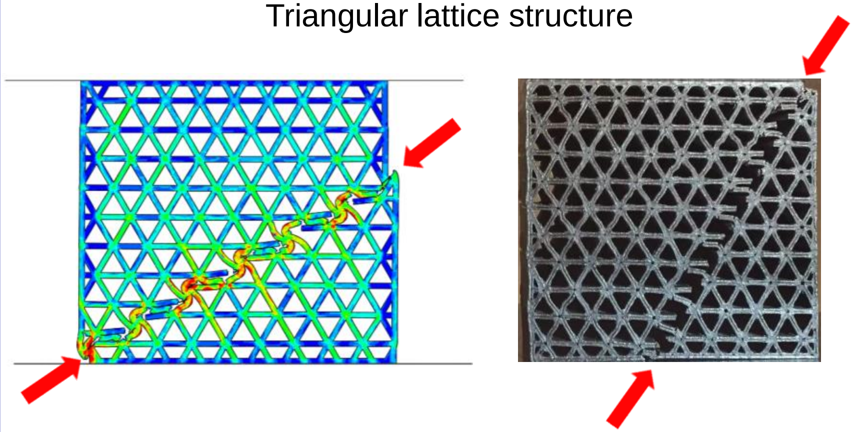


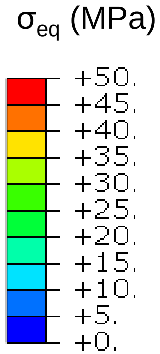


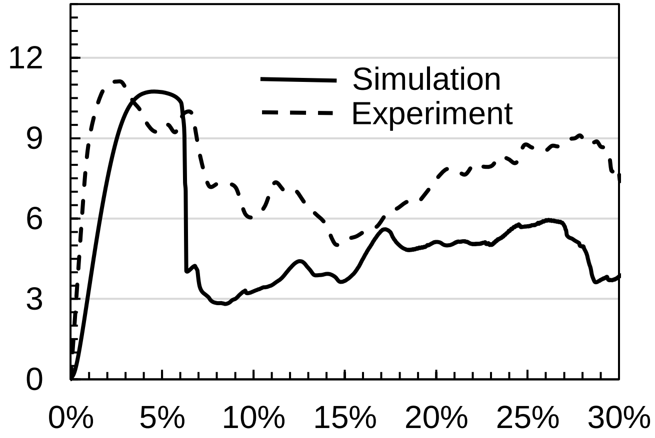
Honeycomb lattice structure



Triangular lattice structure





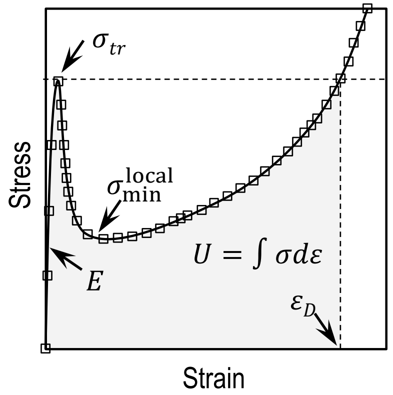


Task 3: Simulations and design optimization using machine learning

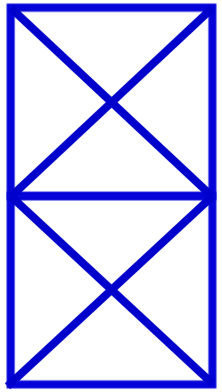
- Sequential integrated ML strategy

Additive Manufacturing enables multi-material lattice design of bumper with multiple conflicting requirements

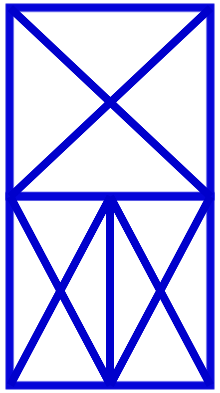
Target Stress-Strain Curve



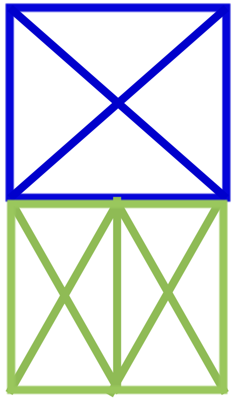
1st Prediction Stage



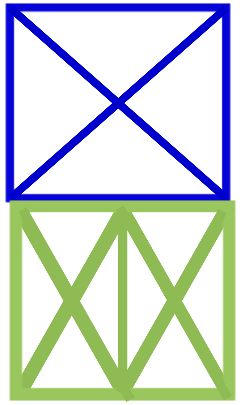
2nd Prediction Stage



3rd Prediction Stage



4th Prediction Stage



1×50 evenly spaced vector $\{X\}$ → Gene type classification → Gene size classification → Material (gradient) classification → Thickness (gradient) classification

Gene type classification → Gene type (Y_1) (1×2 vector) — *Feedback*

Gene size classification → Gene size (Y_2) (1×4 vector) — *Feedback*

Material (gradient) classification → $\bar{\rho}$ gradient (Y_3) (Scalar classifier) — *Feedback*

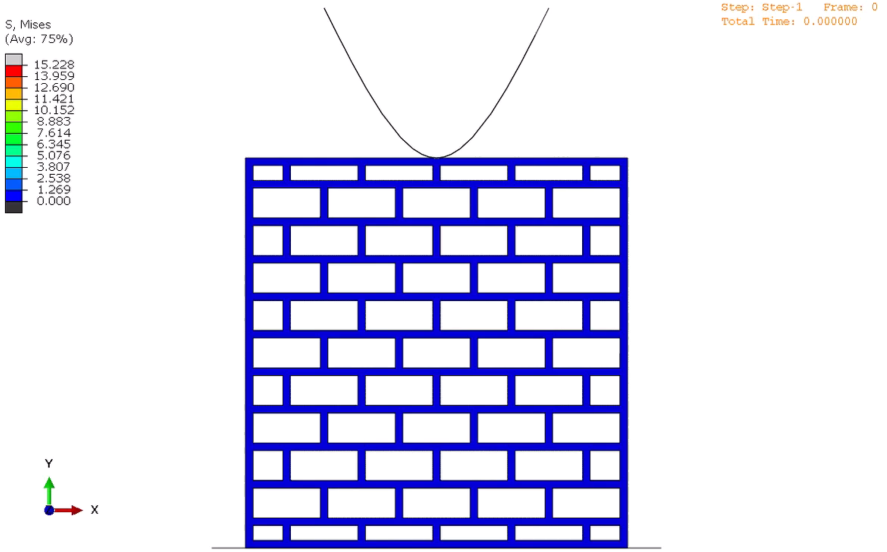
Thickness (gradient) classification → $\bar{\rho}_{\min}$ & $\bar{\rho}_{\max}$ (Y_4) (1×2 vector)

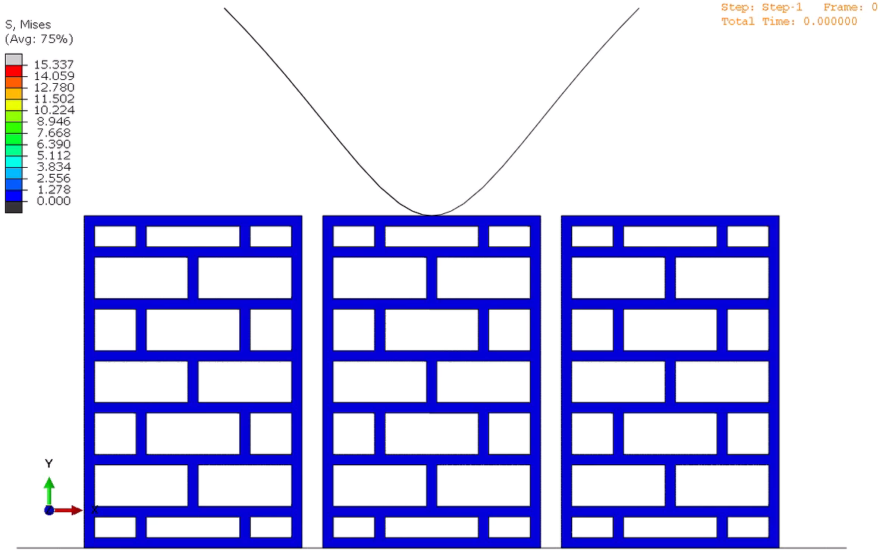
- Input
- Output
- Sequential integrated ML strategy

Task 3: Simulations and design optimization using machine learning

- Evaluating Different Configurations for Bumper Design

- Dynamic response with 11 m/s
- Base material: TMPTA (brittle)





REMARKS:

- Localized deformation realized from both configurations
- Continuous configuration
  - Enabled by the shape of the leg
- Discontinuous configuration
  - Enabled by independently separated lattices regardless of the shape of the leg